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Method and Apparatus for Atomizing Fluids With a Multi-Fluid Nozzle

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TECHNICAL FIELD

The invention relates to a method and apparatus for atomizing liquids. In particular, the present invention relates to a method and apparatus for atomizing liquids during normal operating conditions when a high pressure fluid is available for atomization as well as under start-up conditions when only a low pressure gas is provided. The presented embodiment relates to a method and apparatus for atomizing heavy hydrocarbon fuels such as diesel, as part of a fuel reforming process.

BACKGROUND OF THE INVENTION

Fuel cell technology is an efficient and environmentally friendly power source that has the potential to revolutionize the transportation industry. Unlike fossil fuels that produce undesirable by-products such as sulfur dioxides, nitrogen oxides and carbon monoxide, fuel cells powered by pure hydrogen are virtually emission free. The problem is that although hydrogen exists on Earth in vast amounts it rarely exists in its pure H_2 form. Therefore, one of the keys to bringing fuel cells to the mass market (for example use in vehicles) is finding a pure hydrogen source that is both environmentally responsible and economically

feasible. Some fuel cell cars are being developed to operate on pure hydrogen (produced at off-site plants) that is pumped directly into the car. The drawback of this approach is that it would require the expenditure of hundreds of billions of dollars to create a new hydrogen distribution network.

Using on-board reformers that convert commercially available hydrogen sources like gasoline and diesel to hydrogen are becoming increasingly attractive. The reformation of hydrocarbon fuels releases CO_2 and other gases at substantially lower amounts than existing vehicles. Furthermore, using commercially available fuels as the source of hydrogen would save billions in infrastructure costs.

Catalytic auto-thermal reforming ("ATR") is one of the most effective methods of producing hydrogen from heavy hydrocarbons like gasoline and diesel. In ATR, sub-stoichiometric amounts of air partially oxidize the fuel and liberate heat for the endothermic reactions involving steam. During start-up conditions steam is generally not available and hydrogen is produced by partial oxidation of the fuel. During normal operating conditions the hydrocarbon feed stocks are reformed to a hydrogen rich stream by passing the air, steam, and raw fuel over a catalyst bed in the reformer (See, U.S. Patent No.6,045,772 issued to Szydlowski et al., issued on Apr. 4, 2000). The actual product yield depends on the catalyst, fuel composition and reactor efficiency. In operation a number of factors influence reactor efficiency including: the amount of mixing between the air, steam and fuel, the method of injection of the fuel-steam-air mixture into the reactor, and the pressure drop of air across the system.

One of the most important factors of ATR efficiency is proper mixing of the

fuel, steam and air before contacting the catalyst. Incomplete mixing and gas phase reactions lead to temperature non-uniformities and poor hydrocarbon conversion. Hot spots result if the mixture is locally air rich producing conditions that are favorable for the catalysts to sinter. Coke formation occurs if the mixture is locally fuel rich or lean in H_20, decreasing the efficiency of the reactor.

When reforming heavy hydrocarbons, the method of obtaining a well mixed water-fuel-steam spray and injecting it into the reforming reactor is critical. Previous experience with diesel fuel indicates that heavy hydrocarbons need to be injected directly into the ATR as a liquid, since attempts at vaporization generally lead to coke formation. See, U.S. Patent No. 6,444,179 issued to Sederquist, on Sep. 3, 2002. Optimal efficiency is obtained when the fuel is atomized into droplets of approximately 10μm or finer. Mechanical atomizers are generally limited to producing droplets that are about 50μm, which is too large to provide adequate mixing and coke free operation. Therefore, high pressure, gas assisted atomizers are needed to atomize the fuel into a proper droplet size.

From the standpoint of fuel cell efficiency, it is desirable to minimize the pressure drop of the air across the ATR system and specifically across the spray nozzle. The increased air pressure required to overcome a large air side pressure drop has a high energy cost and negatively impacts system efficiency. For this reason the nominal air drop across the nozzle should be restricted to about 1psi.

Because the power required to pump liquids is much less than that of air, the pressure drops for the atomizing liquid and feed stock can be much higher than the air side drop and are nominally specified to be less than 200psi.

Steam is the preferable atomizing fluid. However, under ATR start up

conditions steam is not available and only air can be used for atomization.

There is a need in the art for a method and apparatus that atomizes heavy hydrocarbon fuels for insertion into an ATR. In particular, there is a need in the art for a method and an apparatus for atomizing heavy hydrocarbons that intimately mixes the air, steam and fuel, produces droplet sizes of around 10μm during normal conditions, limits the air drop across the nozzle to around 1psi, and is operable during both normal and start-up conditions.

Summary of Invention

The three-fluid atomizing nozzle generally comprises a nozzle body and nozzle cap. The nozzle body houses at least three fluid/gas lines including: a feed stock tube (supplying the fluid to be atomized), a high pressure atomization fluid tube (i.e. steam) and a low pressure dispersion fluid tube (i.e. air). The nozzle cap attaches to the nozzle body and forms a mixing chamber where the three fluids mix during normal operation.

Water particularly in the form of steam is the preferred atomizing fluid, however, other fluids capable of atomization could also be used. The feed stock can be any liquid that needs to be atomized. The presented embodiments use air as the dispersion gas, however, other gasses could also be used.

During normal operating conditions the atomizing fluid is fed from the atomizing tube into the atomization cavity of the nozzle body. The atomizing fluid interacts with the feed stock supplied by the parallel feed stock tube. The streams of feed stock liquid and atomizing fluid are oriented in a way to achieve intimate mixing of the two streams. Angling the streams toward each other is one way to ensure proper mixing and to encourage atomization. The flow rates and pressures

of the atomizing and feed stock streams should be at sufficient levels to atomize the fluids into a desired droplet size. Multiple atomizing tubes may used to achieve increased atomization.

A nosepiece located at the convergence of the feed stock and atomizing streams straightens out the atomized feed stock jet. In addition, at startup the nosepiece causes the feed stock to film across the sharp edged surface of the nosepiece.

The feed stock and atomizing streams interact and the atomizing fluid atomizes the feed stock. The resulting atomization fluid-feed stock spray passes through the nosepiece aperture and issues into a mixing chamber that is formed when the nozzle cap is attached to the nozzle body.

A dispersion gas is introduced through the dispersion gas tube that runs parallel to the feed stock and atomizing tubes. As the dispersion gas exits the nozzle body it is forced to turn by the nozzle cap that surrounds the nozzle body promoting mixing between the feed stock, high-pressure atomizing fluid (when available) and low-pressure dispersion gas. The geometry of the cap should allow the dispersion fluid to be directed radially into the atomized feedstock spray. The resulting well mixed spray exits an aperture in the nozzle cap producing a spray with desired droplet size. The diameter of the nozzle cap's aperture determines the extent of mixing between the feed stock, atomizing liquid and dispersion gas.

During start-up conditions (in an ATR) steam is usually not available and atomization must be achieved without the use of a high-pressure atomizing fluid. The three-fluid atomizing nozzle is designed to allow the feed stock to film across the sharp-edged nosepiece. The low velocity dispersion gas radially interacts with

this feed stock film atomizing the feedstock into a slightly coarser spray than achieved under normal conditions when the high pressure atomization fluid is available.

The invention involves supplying a stream of feed stock liquid into a atomization chamber with at least one high pressure atomization jet; orienting the high pressure atomization jet(s) and feed stock streams in a way to achieve intimate mixing of the two streams; atomizing the feed stock stream with the atomization fluid from said atomization jet(s) forming droplets containing a well mixed atomizing fluid-feed stock mixture; directing the atomizing fluid-feed stock spray into a mixing chamber; radially inserting a dispersion air into the mixing chamber, forming a well mixed atomizing-feed stock-dispersion spray mixture.

During start-up conditions where a high pressure atomizing fluid is not available, the feed stock forms a film and the dispersion gas radially contacts the feed stock film atomizing the feed stock into droplets.

When used in conjunction with an ATR, the present invention allows the atomization of a fuel source in both normal and start-up conditions. During normal operations the fuel is atomized with a high pressure steam, forming atomized fuel-steam droplets which are subsequently mixed with air allowing for autothermal reformation of the mixture. During start-up (when no steam is available and therefore no high pressure steam for atomization or for use in the autothermal reaction) the fuel forms a film over part of the nozzle and the fuel is atomized by a radially directed low pressure air source, forming atomized fuel-air droplets allowing reformation of the fuel by partial oxidation until enough steam is generated to proceed with normal operation.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A- is an end on view of the nozzle body;

Fig. 1B- is a side cross-sectional view of the nozzle body;

Fig. 1C- is an end on view of the nozzle cap;

Fig. 1D- is a side cross-sectional view of the nozzle cap;

Fig. 2A- is an end on view of the nozzle body with dimensions;

Fig. 2B- is a side cross-sectional view of the nozzle body with dimensions;

Fig. 2C- is a top on view of the nozzle cap with dimensions;

Fig. 2D- is a side cross-sectional view of the nozzle cap with dimensions;

Fig. 3A- is a cross-sectional view of the nozzle body;

Fig. 3B- is a cross-sectional view of the nozzle cap;

Fig. 3C- is a cross-sectional view of the nozzle cap engaged with the nozzle body.

Fig. 4A- is a graph illustrating the spray characteristics during start-up conditions, specifically count rate (No/s) vs. distance from center of the spray (in);

Fig 4B- is a graph illustrating the spray characteristics during start-up conditions, specifically D30, (μm) vs. distance from center of the spray (in);

Fig. 4C-is a graph illustrating the spray characteristics during start-up conditions, specifically count rate (No/s) vs. distance from center of the spray (in);

Fig. 5A- is a graph illustrating the spray characteristics during low-flow conditions, specifically count rate (No/s) vs. distance from center of the spray (in);

Fig. 5B- is a graph illustrating the spray characteristics during low-flow conditions, specifically D30 (μm) vs. distance from center of the spray (in);

Fig. 5C- is a graph illustrating the spray characteristics during low-flow conditions, specifically mean velocity (m/s) vs. distance from center of the spray (in);

Fig. 6A- is a graph illustrating the spray characteristics during high-flow conditions, specifically count rate (No/s) vs. distance from center of the spray (in);

Fig. 6B-is a graph illustrating the spray characteristics during high-flow conditions, specially mean velocity (m/s) vs. distance from center for the spray (in);

Fig. 6C-is a graph illustrating the spray characteristics during high-flow conditions, specifically D30 (μm) vs. distance from center of the spray (in).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present embodiment relates to a method and apparatus for atomizing heavy-hydrocarbon fuels (in this case diesel) for insertion into an ATR using steam to atomize the fuel at normal operating conditions and air to atomize the fuel during start up.

The present embodiment allows the atomization of a fuel source in both normal and start-up conditions. During normal operations a stream of high pressure steam is used to atomize the fuel, forming atomized fuel-steam spray which is subsequently mixed with air allowing autothermal reformation of the mixture. During start-up (when no steam is available) the fuel forms a film over part of the nozzle and the fuel is atomized by a radially directed low pressure stream of air, forming atomized fuel-air spray allowing reformation of the fuel by partial oxidation until enough steam is generated to proceed with normal operation.

Figs. 1A-D, 2A-D and 3A-C are schematic illustrations of several embodiments of the present three-fluid atomizing nozzle. The atomizing nozzle generally comprises: a nozzle body **1**, nozzle end cap **2**, fuel tube (feed stock) **3**, water/steam (atomizing fluid) tube **4**, and air tube (dispersion gas) **5**.

The parts of the present embodiment were constructed of metal, however, other resilient materials that can withstand the pressures and other stresses associated with atomization could also be used.

The nozzle body **1** of the present embodiment is generally cylindrical in

shape and has a central cavity **9**, as shown in Fig. 3A. The cavity **9** continues into a nosepiece **6** as shown in Figs. 1B and 3A. The nosepiece **6** has a chamber **11** and a central aperture **8**. In the present embodiment the diameter of the nosepiece aperture **8** was approximately 0.05". See, Figs. 1-3. An acceptable range for the diameter of the nosepiece aperture is between 0.010-0.250", preferably between 0.025-0.100". The nosepiece **6** extends out of the nozzle body **1** and serves two purposes: during normal conditions it straightens out the feed stock-atomization spray and second, during start up it allows a film of feed stock to form over it which is then atomized by the radially directed dispersion gas stream.

The nozzle cap **2** is complementary in shape to the nozzle body **1** and engages the nozzle body **1** forming a mixing chamber **7** between the attached nozzle cap **2** and nozzle body **1**, as shown in Fig. 3C. The mating of the nozzle cap **2** and nozzle body **1** can be accomplished in a variety of ways including screwable attachment.

The mixing chamber **7** encourages mixing between the different nozzle fluids. In the present embodiment the nozzle cap **2** screws on to nozzle body **1**, however, other attachment means can be envisioned. The nozzle cap **2** has a central aperture **10**. See, Figs, 1C and 1D. The nozzle cap **2** screws on to the nozzle body until the clearance between the nozzle body **1** and nozzle cap **2** is between 0.175"-0.375", preferably between 0.225"-0.275". A suitable clearance between then nosepiece **6** and nozzle cap **2** is between 0.05"-0.25", preferably between 0.10"and 0.15", Figs 3A-C. These clearances are important because as discussed later, these distances determine the direction and velocity of the

dispersion air when it enters the mixing chamber **7**. If the distance is to large the velocity will not be sufficient to atomize the fuel upon start-up and the air will not be directed radially as needed. If the distance is too small the resulting increase in air pressure drop will decrease efficiency. These distances can be modified according to desired results.

The steam tube **4** has a first and second end **4'** and runs partway through of the nozzle body **1** terminating in the nozzle body's cavity **9**. Figs. 1A,1B, 3A-C. The first end of the steam tube **4** is attached to a steam source such as an ATR reactor and the steam is pumped through the tube by a pump (not shown). The steam tube **4** has defined diameter that narrows at the second end of the tube **4'** to efficiently drop the pressure and increase the velocity of the water/steam being introduced. Fig. 1B. The second end of the steam tube **4'** extends into the nozzle body's cavity **9** and is angled so that the steam exiting the steam tube **4'** is directed toward the center of the nozzle body's cavity **9**, as shown in Fig. 1B. In the present embodiment the second end of the steam tube **4'** is angled at approximately 30° off vertical as shown in Figs. 1B and 3A. The steam tube **4** of the present embodiment has a initial diameter of 1/4" narrowing to a 0.030" passage at its second end **4'**. The diameter of the tube can be modified to achieve desired pressures, velocities, flow rates and other characteristics.

The fuel tube **3** has a first end and second end **3'**, the first end being attached to a fuel source. The fuel is pumped through the fuel tube **3** using a liquid pump assembly. (not shown) The fuel tube **3** runs parallel to the steam tube **4**, the fuel tube **3** can have a narrower diameter at its second end **3'** for maximizing the

stability of the fuel flow rate. Fig. 1B. The second end of the fuel tube **3'** extends into the nozzle body's cavity **9** and is angled so that the fuel exiting the fuel tube **3'** is directed toward the center of the nozzle cavity **9** and into the nosepiece chamber **11**. In the present embodiment the second end of the fuel tube **3'** is angled at approximately 30° off center as shown in Fig.1B. The fuel tube **3** of the present embodiment had a diameter of 1/8" narrowing to a 0.011" passage at its second end **3'**. The angles and orientation of the fuel and steam tubes can be adjusted for optimal performance, preferably keeping their angles between 10 and 45° off center.

The steam and fuel streams meet each other in a small chamber **11** extending into the nosepiece **6**, as show in Figs. 1B and 3A. The steam atomizes the liquid fuel into a fine spray that issues though the aperture in the nosepiece **8** and into a cavity **7** between the nozzle body **1** and the nozzle cap **2**. Fig. 3C. The size of the droplets formed is partially a function of the amount of pressure maintained by the steam tube **4**. To obtain droplet sizes of approximately 10μm it was found that a pressure range (at the first end of the steam tube **4** of between 5-200psig was acceptable, preferably between 10 and 60 psig. Obtaining different droplet sizes can be achieved by altering the pressure of the steam. (*Atomization and Sprays*, Arthur Henry Lefebvre; and *Atomization and Spray Drying*, W.R. Warshall, Jr., American Institute of Chemical Engineers, 1954)

The air tube **5** runs through the body of the nozzle **1** parallel to the fuel **3** and water **4** tubes. Fig. 1B. Unlike the fuel **3** and water **4** tubes, the air tube **5** does not terminate in the nozzle body's cavity **9**. Fig. 3A. Instead the air tube continues

through the nozzle body **1** terminating at the end of the nozzle body **1**. The air flows from an air source, through the air tube **5** and into the cavity **7** formed between the nozzle body **1** and cap **2**. The air is pumped from an air source by an air pump (not shown) The air exits the nozzle body **1** and is forced to turn by the nozzle cap **2** that surrounds the end of the nozzle to promote mixing between the fuel-steam and the air. The geometry of the cap **2** allows the air to be directed radially into the fuel-steam spray. The resulting well-mixed fuel-steam-air spray exits the cap aperture **10** and enters the headspace of a reformer. The diameter of the nozzle cap aperture **10** determines the extent of the mixing between the air and fuel-steam mixture. The smaller the cap aperture **10** the better the mixing, however, at the expense of the air-side pressure drop. In the present invention the diameter of nozzle cap's aperture **10** was 0.25". It was found that an acceptable range for the nozzle cap's aperture was between 0.05 -1", preferably between 0.10-0.50" . In the present embodiment the air tube **5** had a diameter of 3/8". The pressure of the air was maintained around 1psi to maximize efficiency.

The atomizing fluid, feed stock and dispersion tubes can be attached to and mounted within the nozzle body by various means. The said tubes can be pressure fitted, soldered, or otherwise attached to the nozzle body.

The nozzle body chamber, nosepiece and other parts can alternatively be machined out of a solid nozzle body structure. In such an embodiment the various tubes (feed stock, dispersion and atomizing) are channels machined out of the nozzle body. The channels would have a means for attaching to an outside source of gas/fluid. The machined channels could be machined to achieve the same

characteristics as the tubes and achieve similar atomization properties.

The pressures, flow rates, velocities, reactant ratios and other characteristics of the three fluids can be modified to achieve desired results. In the present embodiments the abovementioned characteristics were determined by idealized reformation equations, desired droplet size and other factors. See, J.H. Hirschenhofer et al., *Fuel Cell Handbook,* fourth edition, U.S. Dept. of Energy Office of Fossil Energy. Such characteristics could be altered when the present invention is used for other applications.

Table 1 list exemplary characteristics for a nozzle designed according to the present embodiment. It should be noted that the values in Table 1 are only examples and are not meant to limit the scope of the invention. The Table 1 values may be modified depending on the size of the nozzle used, the fluid being atomized, and a variety of other factors.

Experimental Results

The performance of the present invention was measured using hexadecane (as laboratory simulant for liquid diesel) and air (as a simulant for steam) to determine the droplet size distribution, spatial distribution and velocity distribution across the cross-section of a test chamber fabricated to contain the spray. Since air is used for mixing and as a steam simulant, in order to eliminate confusion the mixing gas will be called the dispersion air and the air simulating steam will be referred to as the atomizing air. The measurements were made with the help of a Phase Doppler Particle Analyzer (PDPA) that uses an argon ion laser for illuminating droplets. The other major components of the test apparatus included the gas and liquid supply, mixing nozzle, a test chamber and liquid recovery and

recirculation assembly. The hexadecane fuel simulant was supplied via a peristaltic pump to nozzle assembly. The atomizing air and dispersion air were supplied from the same lab air source, but through separate valved and instrumented lines that independently controlled the flow rates and pressures.

The liquid and gas flows were combined in the multi-fluid nozzle as described above, and the nozzle was mounted on the top of a lexan chamber to contain the hexadecane spray. The spray in the lexan chamber was characterized by measuring the droplet diameter, droplet velocity and number concentration as a function of spatial location with PDPA. The probe volume of the PDPA was set to characterize the spray at a distance of 2" below the outlet of the nozzle cap. This was determined by the diameter of the spray as a function of the distance from the nozzle. It was deemed desirable to measure the spray at the location where the diameter of the spray was approximately equal to the diameter of the reformer monolith. Since the diameter of the reformer used was 1.5", measurement position increments of 0.25" was considered sufficient to characterize the sprays. Spray characteristics were determined for start-up, low flow and high flow conditions.

During start-up steam is not available but liquid water has to be introduced gradually until it turns to steam in one of the ATR heat exchangers. Optionally, the present nozzle can nebulize liquid fuel and liquid water with the help of atomization air. The hardware does not change. We simply bring in liquid water through the steam pipe. The two streams fill up the cavity and form a film that is broken up by the dispersion air. The mechanism is exactly the same as being used in the start-up mode with liquid fuel and air. This way steam can be created during startup and a separate steam generation means is not necessary.

Table 1

	Liquid Flow	Atomizing Gas Flow	Dispersion Gas Flow	Atomizing Gas Pressure	Dispersion Gas Pressure	H_2O/C Ratio	O_2/C Ratio	D30	Mean Droplet Velocity
Design	10cc/min	21 slpm	75slpm	51 psig	1 psig	1.5	0.5	8.3+-2.7μm	10.7+-14.1m/s
Max Turndown	3cc/min	6.3 slpm	25 slpm	10 psig	0	1.5	0.5	8.0+-2.3μm	4.3+-6.1m/s
Start-Up	10cc/min	0	75 slpm	0	1 psig	0	0.5	11.3+-1.2μm	

Example 1-Start-Up Conditions

At start-up conditions the hexadecane spray was only visible using special lighting techniques. With white backlighting the spray was observed as a low density, fine shower spray. Laser light visually indicated a relatively uniform scattering intensity across the entire 4" width of the lexan chamber. Here the atomizing (steam simulant) was not used because steam is not available during start-up condition and the dispersion air was supplied at a pressure of 1 psig.

The PDPA data is summarized in Fig. 6A-C. At 2" from the nozzle, the average droplet count rates were 7010 particles/s, 8410 particles/s and 9410 particles/s over the central 1.5", 1" and 0.5" of the spray, respectively. The corresponding standard deviations were 49%, 37% and 27%. The mass median diameters (MMD) of the droplets, as measured by the PDPA, averaged over the same three regions are 18.9 ± 3.4 μm, 19.4 ± 3.5 μm, and 19.2 ± 2.6μm. When corrected for edge effects and fit to a log normal distribution, the MMD becomes 11.3 ± 1.2μm, 11.5 ± 1.3 μm, and 11.6 ± 1.6μm, respectively. The maximum droplet velocity measured was 22.4m/s and occurred slightly off axis. As expected for an expanding spray jets, Figs. 6A-C show that the central portion of the spray contains the majority of the droplets, the larger droplets, and the faster droplets. The smaller droplets were slower, fewer in number and were found at the periphery of the spray.

The velocity field in Figs. 6A-C clearly show the existence of circulating eddies near the walls of the chamber. The eddies are asymmetric with respect to the x and y axes partly due to the manner in which purge gas was introduced into the chamber to prevent the fine spray from collecting on and fogging up the walls.

The data also suggest that the finer droplets detected at the spray edges are entrained in these eddies. The extent of the recirculation will be smaller in the ATR for which the nozzle is designed. One reason is that the reactor is smaller in size, 1.5" in diameter v. 4" for the lexan chamber. Also, the axial pressure drop across the catalytic bed will cause the flow to straighten and become more uniform at the top of the reactor.

Example 2-Low Flow

In the low flow mode (3cc/min fuel flow rate, 7.1 slpm atomization gas flow rate and 25 slpm dispersion gas flow rate), the nozzle produced a fog like spray that was immediately visible in the test chamber. The appearance of the fog is indicative of the presence of fine droplets generated with the high pressure (10psig) atomizing air. Just upstream of the nozzle, the supply pressure of the atomization air was 10psig and the dispersion air was about 1psig. See Figs 5A-C. For the PDPA data. The average droplet count rate over the central 1.5" of the spray at 2" from the nozzle was measured to be 7625 particles/s, which is slightly higher than at start-up flow. A standard deviation of 37% implies a more uniform spray than under start-up conditions. These measurements are consistent with the visual observations of the low flow spray. The average droplet count rates over the central 1" and 0.5" of the spray were measured to be 8500 particles/s and 8550 particles/s, respectively, with standard deviations of 32% and 25%.

The average MMD of the droplets in the central 1.5" of the spray was 11.8 ± 3.3μm while the corrected and fitted MMD was 8.0 ± 2.3μm. The MMD when averaged over the central 1" of the spray increases to 12.8 ± 2.3 μm (8.4 ± 2.5μm fitted). The MMD averaged over the central 0.5" of the spray is 14.5 ± 3.0μm (9.5 ±

2.4 μm fitted). The measurement of the smaller diameter droplets for the low flow conditions compared to at start-up is consistent with visual observations and atomization theory. The maximum droplet velocity was measured as 16.7 m/s and occurs on axis. This velocity is lower than the maximum measured start-up flow velocity because the dispersion air through the nozzle in the low flow test is only one third of that at the start-up.

Example 3-High Flow

Visually, the nozzle produces an even denser fog under high flow rate conditions. The fog is immediately visible without added illumination. The PDPA data for the high flow rate spray is summarized in Fig. 4A-C. The average count rate over the central 1.5" of the spray is only 1951 particles/s, which is much lower than either start-up or low flow count rates. This is attributed to the density of the fog. It is well known that the signal scattered out of the probe volume can be subsequently scattered out of the receiving optics by particles outside the probe volume. It follows that the greater the spray density, the higher the probability of signal loss. Another mechanism that causes reduced count rate at high number densities is the increased probability of two or more particles being located within the probe volume simultaneously. Anytime two ore more particles are in the probe volume at the same time, the received signal is a composite of all the individual signals from each particle in the volume. The signals cannot be deconvoluted so the PDPA software rejects the signal completely, reducing the count rate. However, the standard deviation of 34% is still believed to be indicative of the uniformity of the spray.

The MMD over the central 1.5" of the spray was measured at 11.4 ± 2.6μm

and the corrected and fitted value is 8.3 ± 2.7μm. The average MMD over the central 1.0" of the spray is measured as 12.5 ± 2.3μm (9.4 ± 2.4μm fitted) and is 13.6 ± 1.8μm (10.7 ± 2.0μm fitted) in the central 0.5" of the spray. These measurements are consistent with the measurements in the low flow case and with visual observations. However, if the first hypothesis that explains the reduced count rate is correct, it would imply that the particle size measurements might also be affected. Since smaller particles produce a weaker signal, signal loss due to scattering from particles outside of the probe volume, it also follows that the signals from the smaller particles are more likely to be lost to the receiving optics. If the second hypothesis is dominant, then the count rate would be reduced, but the size of the data would still be valid. Considering the uncertainty of these factors, it is reasonable to treat the size data as an indication of the largest size distribution that can be produced by the nozzle under the high flow conditions, but that the actual size distribution might be smaller.

Having described the basic concept of the invention, it will be apparent to those skilled in the art that the foregoing detailed disclosure is intended to be presented by way of example only, and is not limiting. Various alterations, improvements, and modifications are intended to be suggested and are within the scope and spirit of the present invention. Additionally, the recited order of the elements or sequences, or the use of numbers, letters or other designations therefore, is not intended to limit the claimed processes to any order except as may be specified in the claims. Accordingly, the invention is limited only by the following claims and equivalents thereto.

All publications and patent documents cited in this application are

incorporated by reference in their entirety for all purposes to the same extent as if each individual publication or patent document were so individually denoted.